FUTURE FLOODING IN HOUSTON: MODELING THE IMPACTS OF CLIMATE AND LAND COVER CHANGE ON HYDROLOGY IN THE BUFFALO-SAN JACINTO WATERSHED

An Undergraduate Research Scholars Thesis

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ABSTRACT

Future Flooding in Houston: Modeling the Impacts of Climate and Land Cover Change on Hydrology in the Buffalo-San Jacinto Watershed. (May 2013)

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Understanding the hydrology of a watershed is essential for both water resource management and public safety, especially flood prevention and mitigation. Both climate change and urbanization have been shown to increase flooding, especially in urbanized watersheds such as the Buffalo-San Jacinto in southeast Texas. Understanding future changes in this watershed will help city planners in the Houston metropolitan area make decisions about the safety of populations during flooding events. Much of the current literature examines only the impact of urbanization or climate change on the hydrologic cycle, but does not consider the joint impact of projected changes. This study performs a sensitivity analysis to examine how future changes in land use and precipitation will influence hydrology in the Houston area by using the Variable Infiltration Capacity (VIC)

macroscale hydrologic model. Climate change scenarios are used to adjust historical precipitation data while land cover is simulated for increased urbanization. The model demonstrated that the increases in these factors cause an increase in runoff, and thereby peak flow and discharge, within the Buffalo-San Jacinto watershed, and that LULC change has a larger impact upon annual runoff while climate change appears to have a greater effect on individual storm events. This means that flooding events will be more frequent and severe, and that occupants close to waterways within the watershed should account for changes in the areas of engineering and property insurance rates.

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NOMENCLATURE

LULC	Land Use/Land Cover
VIC	Variable Infiltration Capacity Model
DEM	Digital Elevation Model
USGS	United States Geological Survey
HUC	Hydrologic Unit Code
LAI	Leaf Area Index

CHAPTER I

INTRODUCTION

Understanding the hydrology of a watershed is essential to both water resource management and public safety, especially flood prevention and mitigation. This is especially true for watersheds in urban areas with high populations that are both dependent upon the watershed for municipal water supply as well as adversely affected by flooding. The hydrology of these watersheds is changing rapidly, due in large part to climate change and urbanization. Understanding future changes due to climate and LULC will be essential to help city planners make decisions for the safety of populations during flooding events.

Both climate change and urbanization are conceptualized as intensifying contributing factors to flooding: precipitation and runoff, respectively. Heavy precipitation events are expected to become more frequent and intense due to increased atmospheric concentrations of greenhouse gases and higher temperatures (Frei et al., 1998; Pachauri, 2008; Meehl et al., 2000; Wentz et al., 2007). These effects are expected both for convective storms (Fowler and Hennessy, 1995; Gordon et al., 1992) and tropical cyclones (Knutson and Tuleya, 2004). The increase in overall precipitation is characterized by increases in the top ten percent of heavy precipitation and decreasing lower intensity events, leading to greater risk of both floods and droughts (Shiu et al., 2012). In Texas, downscaling global climate models has indicated that surface temperature should increase by around 3 K over the next century; however, the models do not agree on the impact on precipitation, some showing general drying or steady precipitation trends with at least one other showing a wetting trend (Jiang and Yang, 2012). Jiang and Yang (2012) also note that precipitation in East Texas shows a slight increasing trend in precipitation and the uncertainty inherent in the climate simulations used while Wentz et al. (2007) note that despite possibly drying trends regionally, a general increase in precipitation with increased temperature has been observed historically and should be expected with continued climate change.

LULC change in the form of urbanization increases the amount of impervious surface within a watershed, which decreases infiltration. Urbanization has been shown to increase runoff and discharge as well as decrease runoff confluence time (Boschl et al., 2007; Olivera and DeFee, 2007; Sheng and Wilson, 2009; Shi et al., 2007). Within a portion of the Buffalo-San Jacinto Watershed, Olivera and DeFee (2007) identified that the annual runoff depth depended primarily on annual precipitation depth and developed area. The White Oak Bayou watershed demonstrated that initially, a watershed maintains an ability to assimilate urbanization within its borders without significant changes in overall watershed hydrology. After reaching a critical mass of urbanization, which occurred in 1973 for White Oak Bayou and was characterized mainly by connecting previously developed areas more than the creation of new development, runoff increases linearly with developed area (Olivera and DeFee, 2007).

Combined, these factors make a watershed more susceptible to flooding and may have a compounding effect on the susceptibility of a community to more frequent and/or intense flooding events. Currently published literature examines both the impact of urbanization and climate change on different aspects of the hydrologic cycle (Cuo et al., 2009). These include the impacts of urbanization on runoff and flooding (Olivera and DeFee, 2007; Shi et al., 2007) and the impact of warmer temperatures on changes in the frequency and intensity of precipitation and flood risk, as well as modeling these changes for daily precipitation and precipitation derived from tropical cyclones (Hamlet and Lettenmaier, 2007; Knutson and Tuleya, 2004; Meehl et al., 2000). Only one study addresses the combination of these two factors. It is retrospective in nature, modeling the previous century (Cuo et al., 2009). This leaves a clear gap in the literature for modeling the combination of these two factors in a prospective manner. Herein I examine the combination of these two factors, urbanization and climate change, on hydrology at a watershed-scale during intense precipitation events and the implications of these changes for future flooding using a sensitivity analysis of the Buffalo-San Jacinto Watershed.

CHAPTER II

METHODS

Study area

The Buffalo-San Jacinto watershed of Southeast Texas (USGS HUC 12040104, shown in Figure 1), which intersects Fort Bend County, Waller County, and Harris County, is home to Houston, TX (US EPA, 2012).

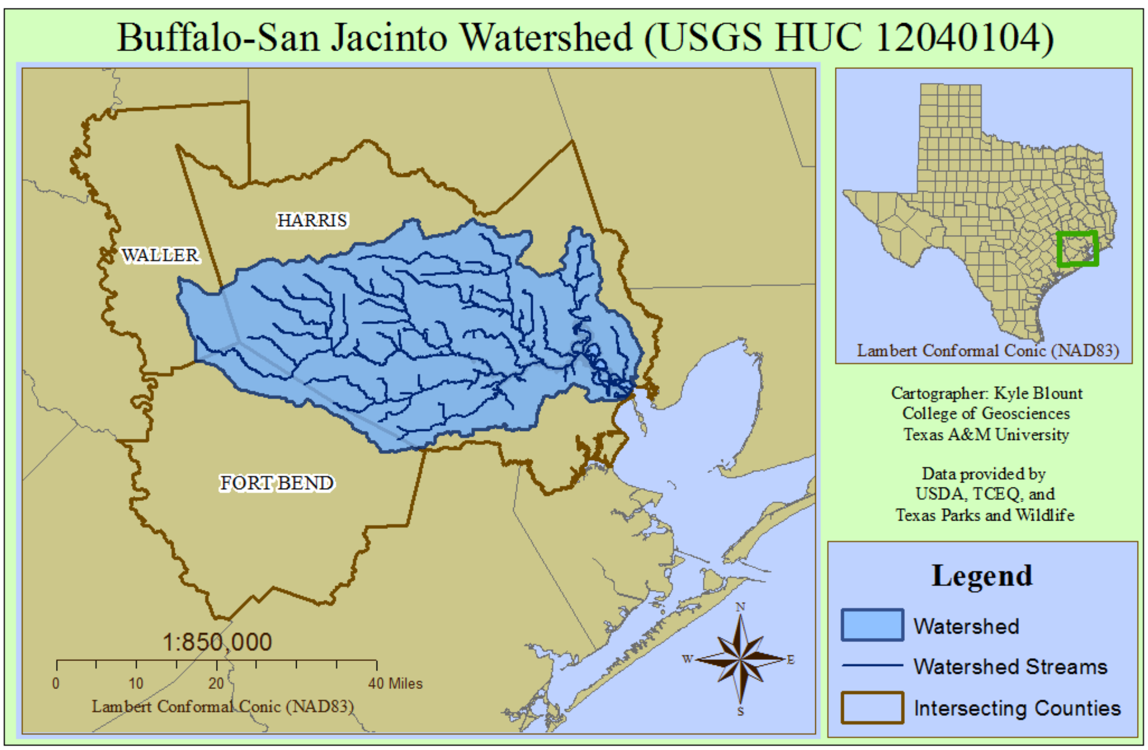

Figure 1: The Buffalo-San Jacinto Watershed.

Houston was recently rated as the fourth fastest growing city in the US with a current population of 6.23 million and a growth rate of two percent (Fisher, 2012). Harris County is also one of the fastest growing counties in the United States (Kever, 2012). This increase in population will undoubtedly lead to increased urbanization within the watershed. This growth, along with its proximity to the Gulf of Mexico and frequent tropical cyclone activity, puts the watershed at an increased risk of flooding from both intensified precipitation as a result of climate change and increased runoff from urbanization. Thus, the Buffalo-San Jacinto Watershed is an area that is ideal to study the combination of these factors and flooding. It represents a watershed in need of models of future scenarios in order to plan for such changes affecting large populations.

Model

The Variable Infiltration Capacity is a semi-distributed macroscale hydrologic model that balances both water and surface energy budgets within each grid cell of the model (Gao et al., 2010). It accounts for subgrid variability in land surface vegetation class, soil moisture storage capacity, and base flow.

The VIC model uses input data consisting of (1) daily meteorological forcing data, consisting of maximum and minimum temperature, precipitation, and wind speed, (2) a soil parameter file, containing location and soil characteristics including infiltration, depth of each soil layer, and saturated hydraulic conductivity, (3) the vegetation library file, which describes each vegetation class in terms of such variables as LAI, albedo, and roughness, and (4) the vegetation parameter file, which indicates the types and fractions of vegetation types as root depth. Using this data, VIC outputs daily fluxes for each grid cell in the model. The VIC routing model uses (1) the fluxes produced by VIC, (2) a fraction file, indicating for each grid cell what fraction of the cell is occupied by the watershed, (3) a flow direction file produced using a DEM indicating which direction runoff from the entire cell moves, (4) a station location file indicating at which point in the watershed the output runoff is calculated, and (5) an impulse response file containing hydrologic parameters. The output of the VIC routing model is the average runoff depth over the basin, which can either be normalized for basin area and turned into discharge data or used by itself as a representation of discharge.

One limitation to the model however, is that it does not account for impervious surface in urbanized watersheds. Instead a bare soil, or no vegetation, parameter is used. Though not ideal, the loamy and clay soils present in the study region possess poor infiltration rates, as do impervious surfaces, so the impact of the inability to account for impervious surfaces should be minimal.

The model was chosen because it is relatively simple to run, easy to manipulate data for multiple model runs, and is widely used in literature for modeling watershed hydrology, making it a useful and familiar choice for such simulations; The VIC model has been used extensively in literature to model a variety of watersheds and has been calibrated accurately to a large variety of these watersheds (Gao et al., 2010). A detailed description of VIC is provided in Liang et al. (1994, 1996, 1996). The source code for the model is available for download online as well as instructions for preparing the model input data (Hydrology, 2009).

Input data and model use

In order to define the spatial extent of the watershed, a shapefile of all of the 8-digit HUC entities was downloaded and opened in ArcMap (USDA, 2013). A new layer was created from a selection of the Buffalo-San Jacinto Watershed, and finally a raster grid file 0.125-degree by 0.125-degree grid cells was produced around the watershed, producing 33 grid cells to be used in the model, as shown in Figure 2.

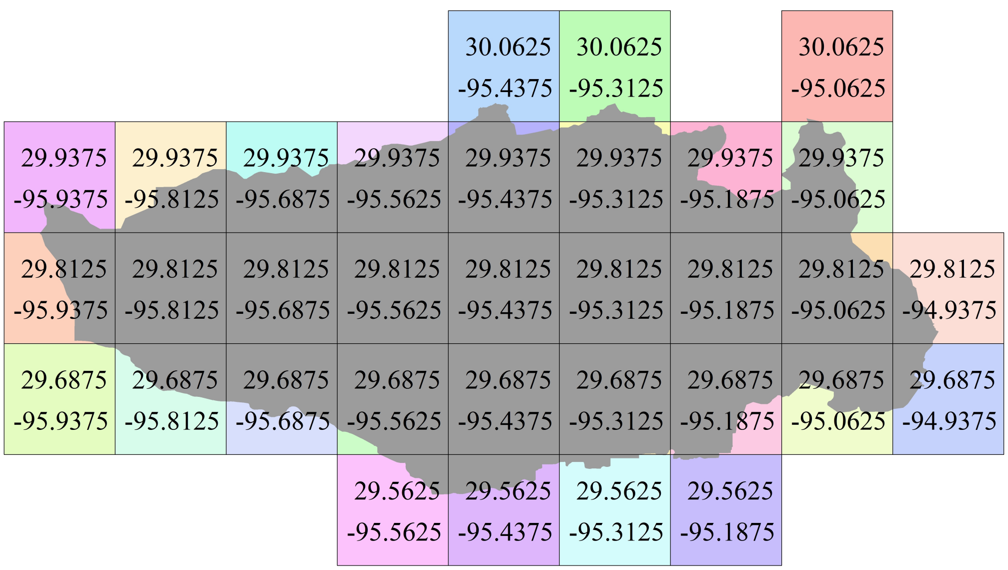

Figure 2: Grid cells used in the model. These thirty three 0.125 degree grids cells intersect the watershed and were used in the VIC model. Image produced by Liang Chen.

The meteorological forcing data as well as soil and vegetation parameter data, already recorded for 0.125-degree grids, were matched to each of the grid cells. These input data files were obtained from the data sets produced for use with the VIC model at a one-eighth degree spatial resolution and available for download on the VIC website by Maurer et al. (2002). The data is provided for each grid cell on a daily basis and includes meteorological forcing data, containing precipitation, maximum temperature, minimum temperature and wind speed; soil parameter data, including soil texture; vegetation library file, which describes each available vegetation type and assigns it an integer value; and vegetation parameter data, which includes vegetation type, factional area, rooting depths, and LAI. Each grid cell is represented by one data value for each variable for the entire cell, and the latitude and longitude of the center of each grid cell is used to refer to the whole grid cell.

In order to create the different experimental conditions, or model runs, the input data files were adjusted for different precipitation, temperature and LULC scenarios. Wentz et al. (2007) suggest that climate change will bring a 7% increase in precipitation per K increase in temperature, and note an approximately 0.2 K decade^{-1} warming trend. When accounting for climate change, simple increases in precipitation and temperature were used to revise to the forcing data, creating scenarios of varying degrees of climate change representing low, moderate, and high change. These scenarios are account for a century of change from when the data was collected (i.e., 1980-1983), so they model climate in 2080-2083. Because this is ten decades later, warming is presumed to increase temperature by 2 K and therefore increase precipitation by fourteen percent. This was used as the moderate change scenario. Increases of 1.5 K and 11.5% precipitation as well as an increase of 2.5 K and 17.5% precipitation were used to model the low and high change scenarios, respectively.

For LULC change, the basin is already highly urbanized, and is likely to be classified as 100% urban land cover, despite some green space, by the 2080's. This factor, combined with the VIC model's use of bare soil in place of impervious or urbanized area, would indicate that a land cover of 100% bare soil would be a reasonable estimate for land cover in the simulation of 2080-2083. Therefore, the vegetation parameter files are adjusted for completely bare soil.

Once these data were collected, manipulated, and the input files created, eight combinations of data or experimental conditions were created: those with vegetation and no, low, moderate, and high climate change as well as those with bare soil and each of the four climate change scenarios. For each of the eight model runs, the global parameter file was edited to match the input data locations, correct output data file locations, correct beginning and ending date for the model and beginning date of the forcing data, and wind speed measurement height, and the VIC model was run using data from the years 1980 to 1983. The data from the year 1983 is utilized for the modeling because it encompasses the landfall of Hurricane Alicia, a category 3 storm, over the Houston metropolitan area in August, providing an example of storm runoff from tropical cyclone activity for the model; while the data for 1980-1982 is used as "spin up" years, allowing the model to calibrate initial 1983 conditions for factors such as antecedent soil moisture.

In order to produce discharge data, the fluxes produced from the VIC model must be run through the routing model. In addition to these flux files, input files for fraction, flow direction, impulse response, station location, and the input parameter files must be created. The fraction file represents the percent of a grid cell that contributes to the watershed, and is determined easily in ArcGIS using Spatial Analyst tools. The flow direction file was created in ArcGIS using a 1-kilometer DEM (USGS, 2013) and the flow direction tool in the hydrology component of the Spatial Analyst tools, as shown in Figure 3. Once each cell had a flow direction, the grid cells were reclassified based upon the routing model specifications, from one to eight, representing north, northwest, east, southeast, south, southwest, west, and northwest in that order. The impulse response file was copied from suggested parameters on the VIC website (Hydrology, 2013). The station location file identifies the grid cell containing the point, or points, at which discharge is calculated. Here, only one station is used for discharge of the entire watershed and is located in the (29.6875, -94.9375) grid cell. For each of the eight model runs, the input parameter file was edited with the locations of the input flux files and output folder, and then the routing model was run, producing discharge data for each of the experimental conditions.

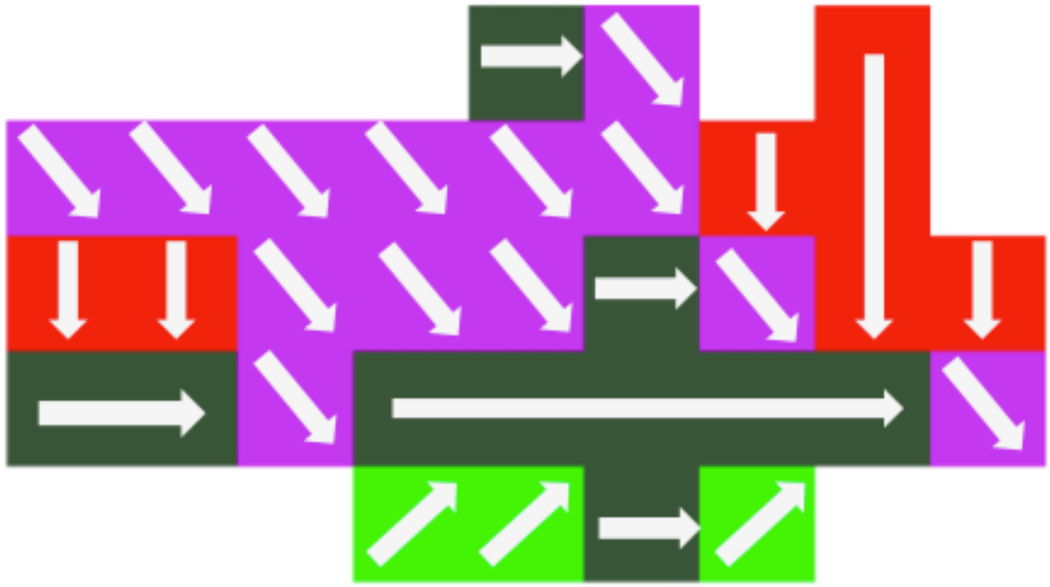

Figure 3: Graphical Representation of the Flow Direction File. Each grid cell is color coded for flow direction (purple = southeast, green = east, red = south, and lime = northeast). Image produced by Liang Chen.

CHAPTER III

RESULTS

Model outputs and validation

The routing model produced runoff depth, shown in graphical form in Figure 4.

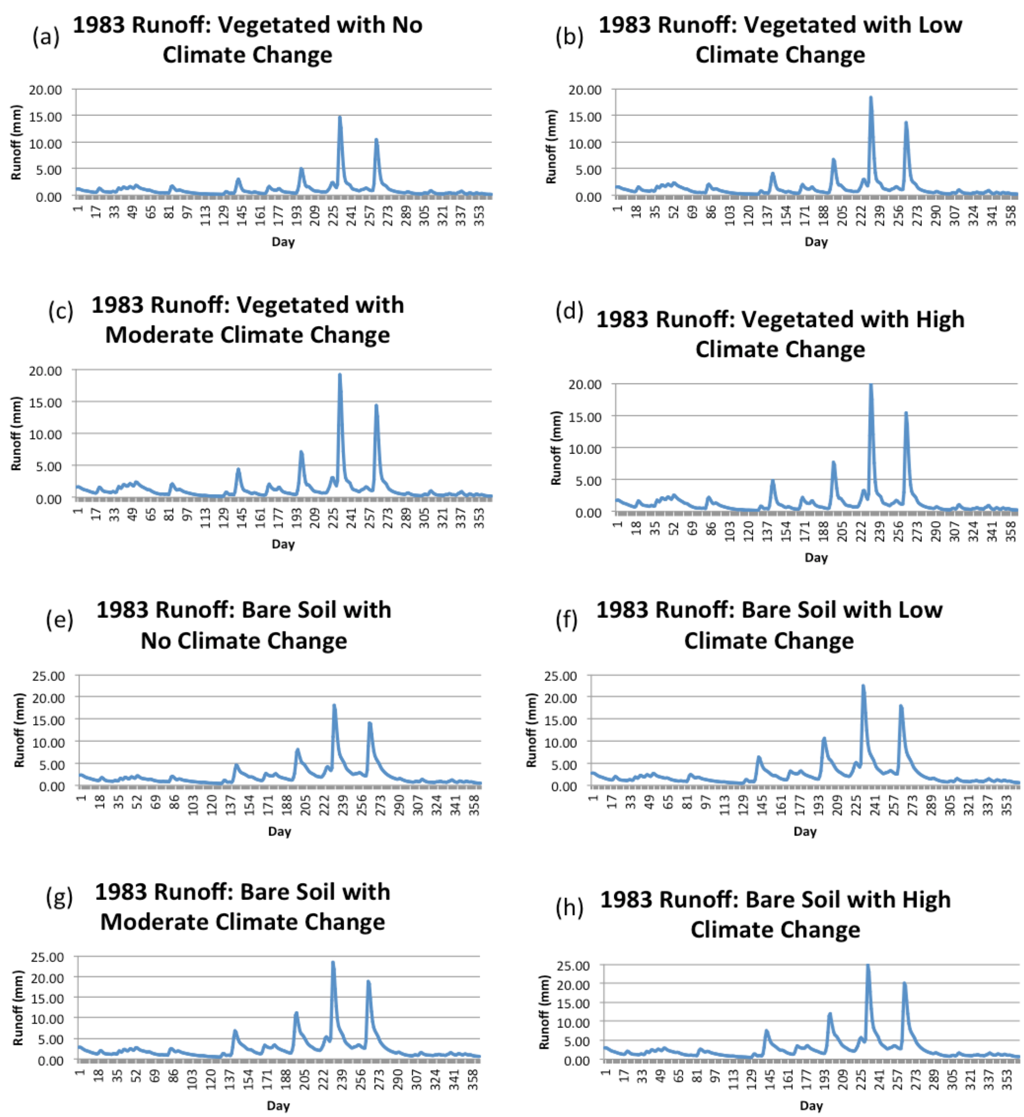

Figure 4: Routing output for each of the eight model runs, (a)-(h), during 1983.

In order to validate that these results accurately represent hydrology in the basin, I compared the runoff depth to discharge in the basin over the same year. Unfortunately, there is no gaging station at the mouth of the basin, so the discharge at USGS gaging station 08073600, shown in Figure 5, was compared to the original 1983 conditions, vegetated with no climate change, and was found to have R^2=0.43063 (Figure 6). It should be noted that discharge is influenced by baseflow and throughflow in addition to runoff. Noting that much of the scatter is located where more discharge is observed than runoff is predicted by the model, this type of scatter is likely caused by increased discharge due to baseflow. Considering the differences in values previously noted and the area represented by these two locations, this can be assumed to be a reasonably strong relationship to show that the model accurately captures hydrology within the basin.

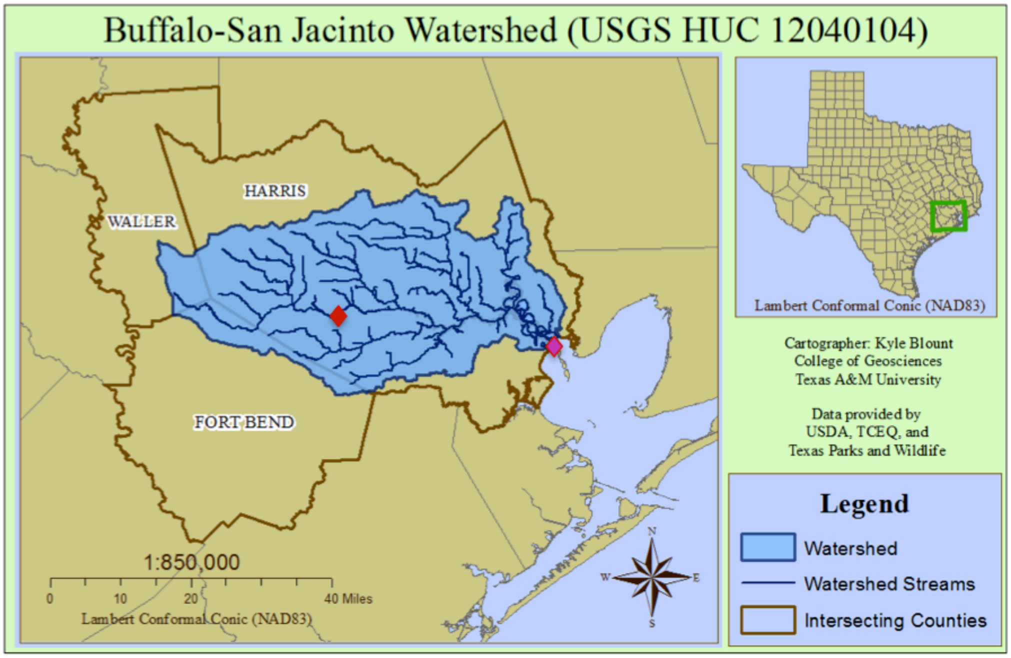

Figure 5: The Buffalo-San Jacinto watershed showing the location of USGS station 08073600, Buffalo Bayou at W Belt Dr, Houston, TX (red) at 29°45'43"N, 95°33'27"W and the model output station (purple).

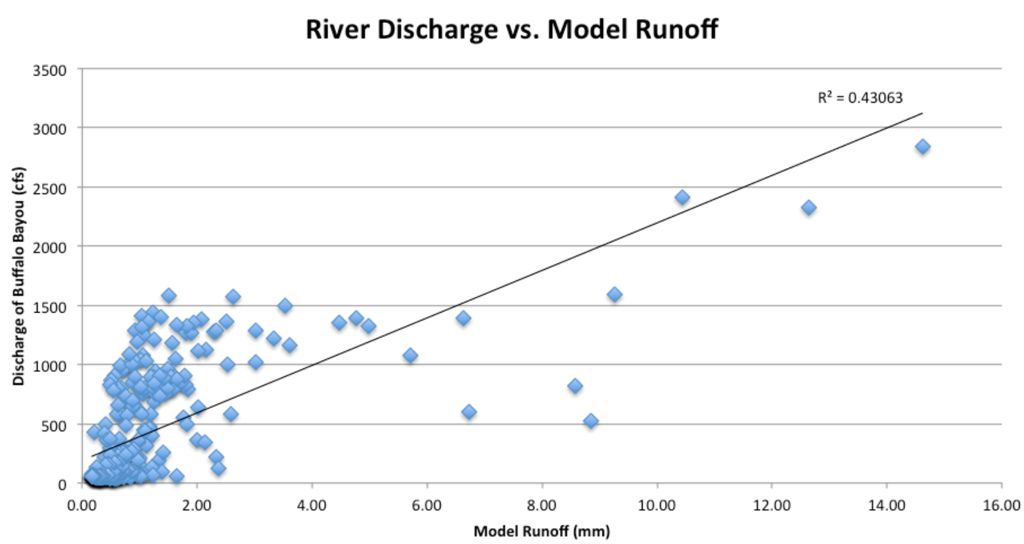

Figure 6: Comparison of discharge for Buffalo Bayou at USGS station 08073600 and modeled runoff depth. Each point (n=365) represents a daily runoff value from the model and a daily discharge record.

Based upon the results shown, two storm events were identified and analyzed (Figure 7). Event 1, with its peak occurring on August 20, 1983, represents the landfall of Hurricane Alicia in the Houston area and a tropical storm event. Event 2, with its peak occurring on September 21, 1983, represents a storm of non-tropical origin.

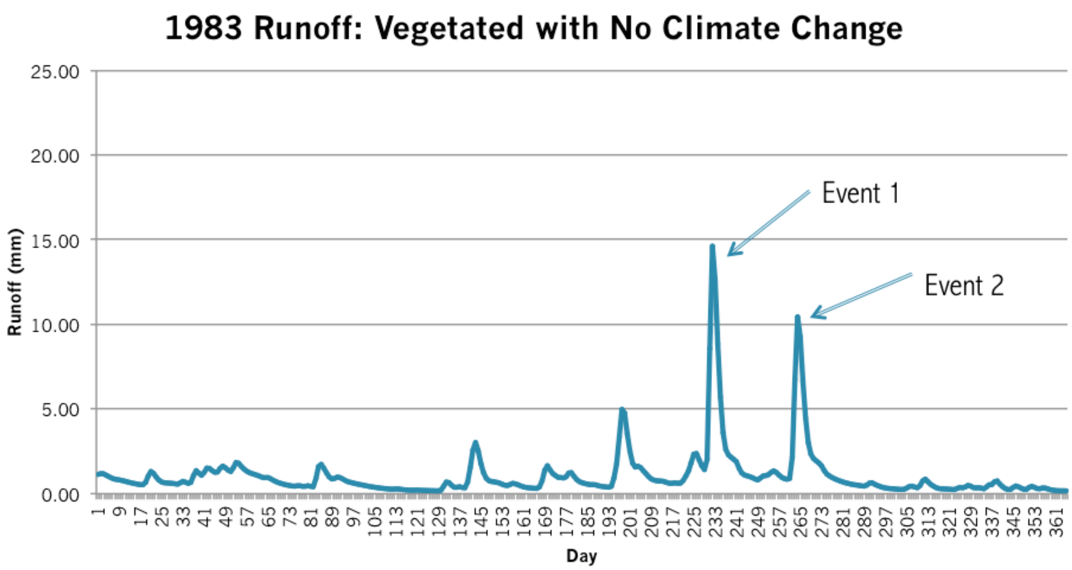

Figure 7: Storm events 1 and 2 identified based upon runoff. The peak runoff from event 1 occurs on August 20 and the peak runoff from event 2 occurs on September 21.

Event 1

The landfall of Hurricane Alicia created the first storm event in 1983. The modeled runoff is represented graphically by LULC (Figure 8) and by climate scenario (Figure 9). As we see in Figure 8, the increase in precipitation and temperature for each climate change scenario produces increasingly larger amounts of runoff. Additionally, we notice that for all four climate scenarios, urbanization, represented here by the transition from vegetated to bare soils, increases runoff for the storm event (Figure 9).

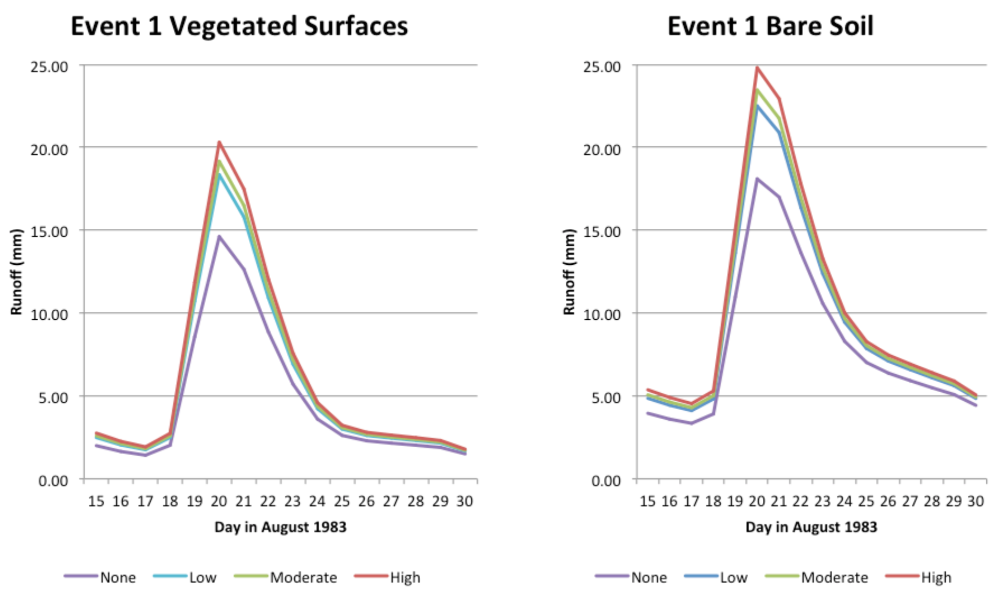

Figure 8: Runoff for the landfall of Hurricane Alicia by LULC type showing the increase in runoff with each increase in climate change scenario.

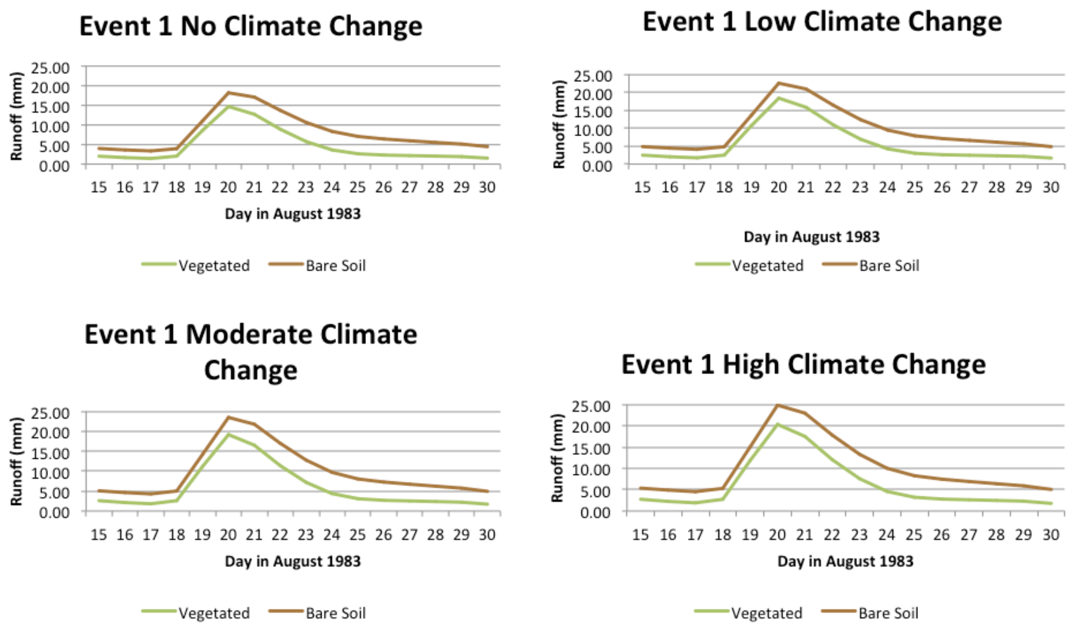

Figure 9: Runoff for the landfall of Hurricane Alicia by climate scenario showing the increase in runoff due to urbanization (the change from vegetated to bare soil).

Event 2

The second storm event occurred in September of 1983, peaking on September 21. The modeled runoff for event 2 is represented graphically by LULC type (Figure 10) and by climate scenario (Figure 11), and the same trends can be observed as were seen in event 1. Urbanization and climate change both increase runoff for event 2.

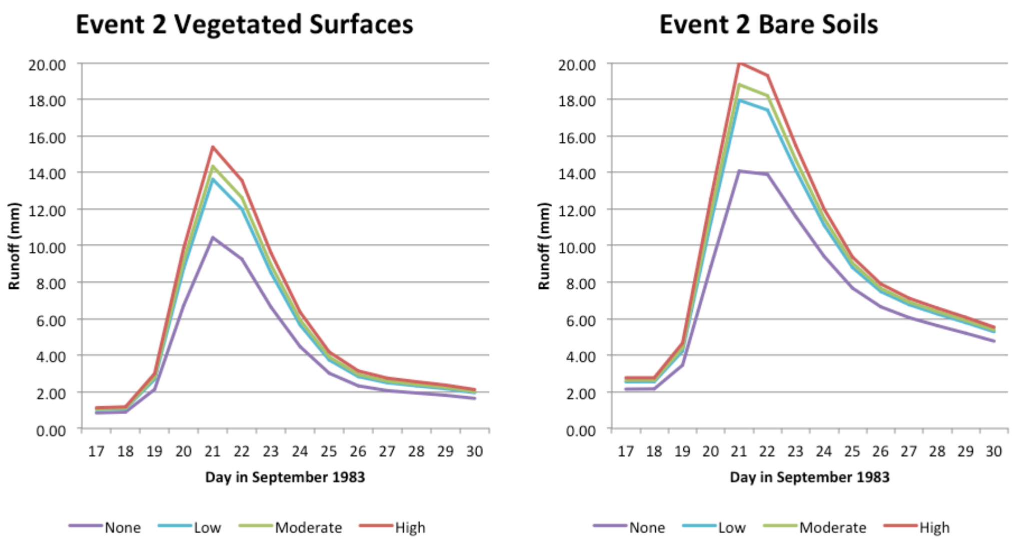

Figure 10: Runoff for storm event 2 by LULC type showing the increase in runoff with each increase in climate change scenario.

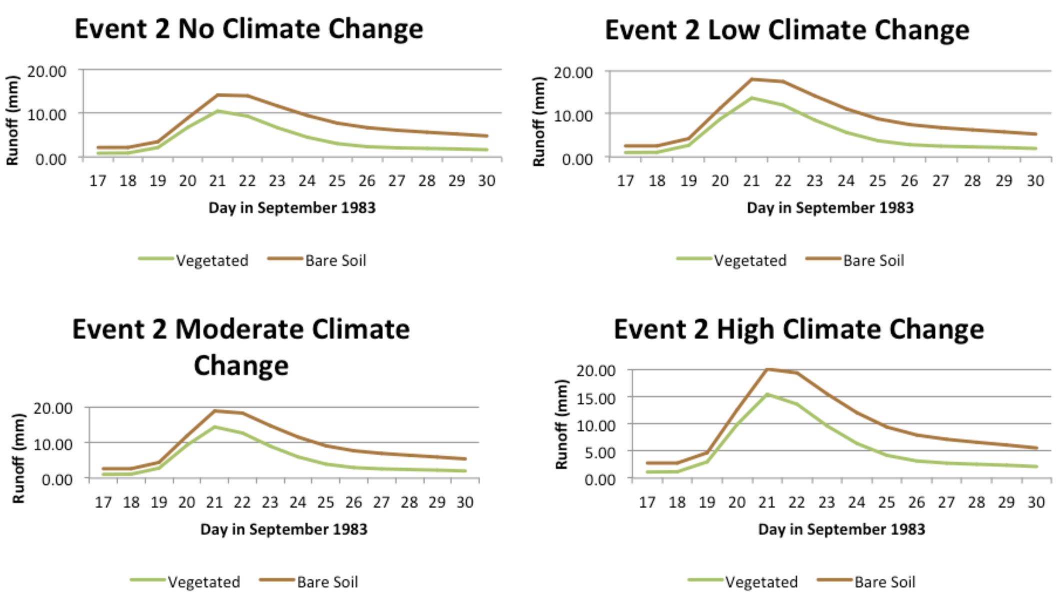

Figure 11: Runoff for storm event 2 by climate scenario showing the increase in runoff due to urbanization (the change from vegetated to bare soil).

Effect of climate change

When examining the individual impact of climate change, we must plot the runoff by climate scenario (Figure 12). Here, runoff is plotted according to climate change scenario. It is important to note that the increase in precipitation is the largest contributing factor for the increased runoff in each of the climate scenarios; however, temperature increase is conceptualized as the driving force behind the increases in precipitation in this study as well as in Wentz et al. (2007).

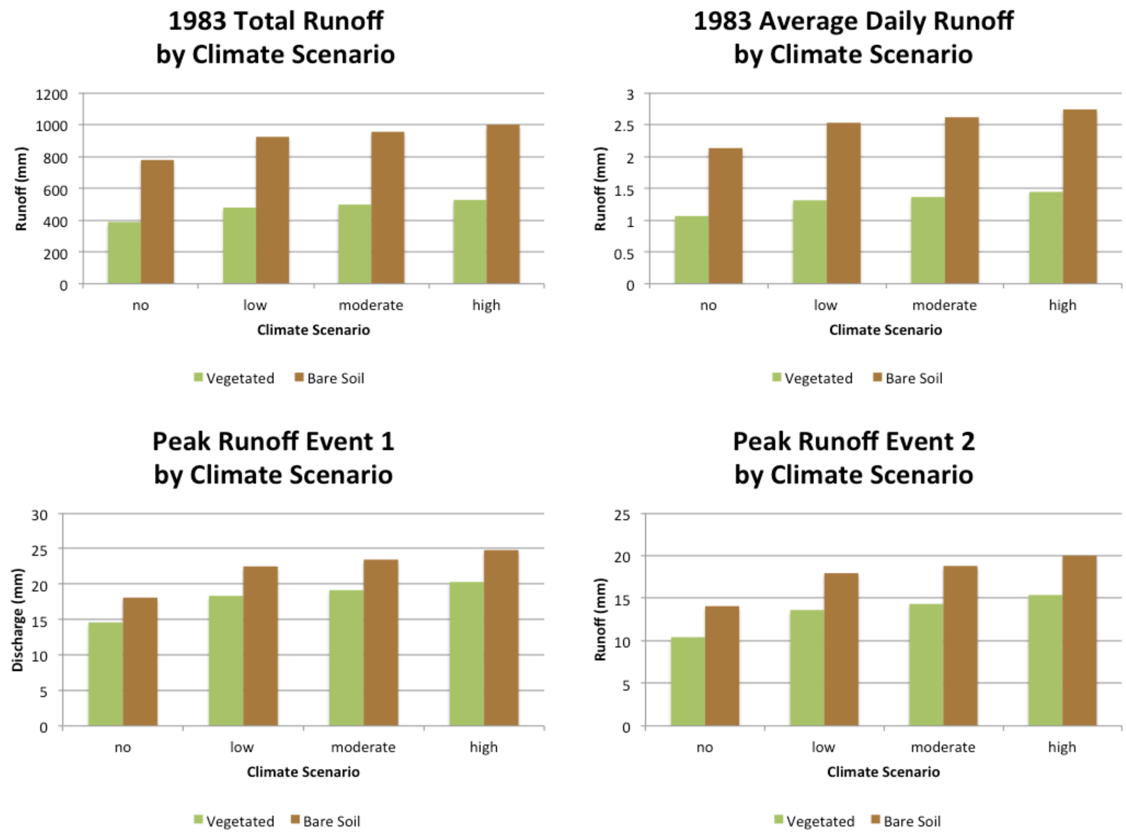

Figure 12: Changes in modeled runoff due to changing climate scenarios for vegetated and bare soils in total 1983 runoff, average daily runoff in 1983, and peak runoff in both storm event 1 and storm event 2. No change represents the control scenario, using the original data from 1983. Low represents a 1.5 K and 11.5% increases in temperature and precipitation, while Moderate and high represent increases of 2K/14% and 2.5K/17.5% respectively.

As can be seen in Figure 12, increasing climate change increases runoff for all time scales considered. A strong linear trend is seen in the increase in runoff with increasing climate change. One Kelvin increase in temperature combined with a 7% increase in precipitation is responsible for an increase in 55 to 89 mm runoff per year, 0.15 to 0.24 mm average runoff per day, or 1.97 to 2.69 mm runoff during storm events.

Effect of LULC change

The impact of LULC change is identified by calculating the average percent increase in runoff due to LULC change (Table 1). This number is determined by calculating the percent increase in runoff between the vegetated and bare soil conditions for each of the four climate scenarios and then averaging these percent increases.

Table 1: Average Percent Increase in Runoff Due to LULC Change.

	Average Percent Increase
1983 Total Runoff	193.69%
1983 Average Daily Runoff	193.69%
Event 1 Runoff	122.79%
Event 2 Runoff	131.96%

LULC change is responsible for a 193.69% increase in total and average daily runoff for 1983, a 122.79% increase in runoff during storm event 1, and a 131.96% increase in runoff for storm event 2.

Combined effects

The individual and combined effects of climate and LULC change are summarized in Table 2. The average increase due to climate change is calculated as the average increase in runoff for vegetated and bare soil conditions when moving from no to high climate change. The total combined changes are calculated as the percent increase from vegetated soil with no climate change to bare soil and high climate change.

Table 2: Combined percentage increase in runoff.

	Average Due to Climate Change	Due to LULC Change	Total Combined Changes
1983 Total Runoff	132.09%	193.69%	257.39%
1983 Daily Runoff	132.09%	193.69%	257.39%
Event 1 Runoff	138.01%	122.79%	169.75%
Event 2 Runoff	144.82%	131.96%	191.78%

Climate change is responsible for a 132.09% increase in total and average daily runoff as well as a 138.01% increase in runoff for event 1 and a 144.82% increase in runoff for event two. Climate and LULC change combine to account for a 257.39% increase in runoff for total and average daily runoff, a 169.75% increase in runoff for event 1, and a 197.78% increase in runoff for event 2.

The interaction of climate and LULC change and climate change shows some interaction between the two factors. Figure 13 shows the percent increase in runoff due to LULC change according to climate scenario. For both total and storm runoff, there appears to be a slight decrease in the runoff increase caused by LULC change as climate change becomes more extreme; however, the effect appears to be greater for total runoff than for individual storm events.

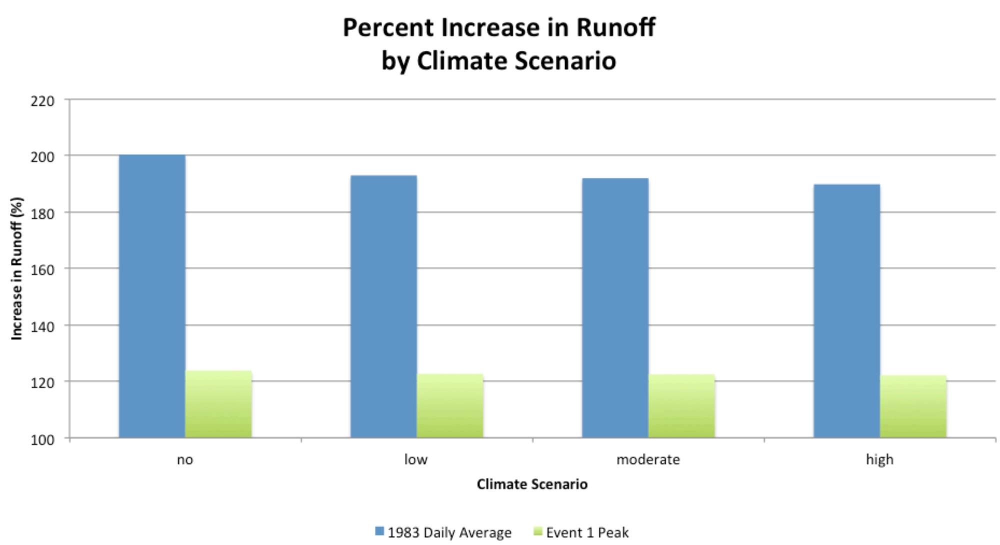

Figure 13: The percent increase in runoff caused by LULC change compared to climate change scenario for total runoff and storm event runoff, represented by storm event 1. No change represents the control scenario, using the original data from 1983. Low represents a 1.5 K and 11.5% increases in temperature and precipitation, while Moderate and high represent increases of 2K/14% and 2.5K/17.5% respectively.

CHAPTER IV

CONCLUSIONS

Both LULC and climate change increased runoff in the models of the Buffalo-San Jacinto Watershed. Though both factors do increase runoff and the potential for flooding, each factor is more significant at differing time scales to varying degrees.

Climate change is responsible for a larger percentage of increased runoff during storm events than it is for total or average runoff over longer time scales. According to the results of this experiment, climate change increases storm discharge by 2.3 to 2.7 mm per K increase in temperature and 7% increase in precipitation for a storm event while only increasing average daily runoff by 0.2 mm. This means that the ratio of increase in precipitation to runoff is approximately 1:2.5. These figures appear to be within the range explored in literature. Legesse et al. (2003) noted a 1:3 ratio in reduction of precipitation to discharge when modeling a basin in Ethiopia while Chen et al. (2007) noted a ratio of 1:1.5 for increase or decrease of precipitation to runoff when modeling the upper Hanjiang basin in China. Additionally, climate change is responsible for larger increases in storm runoff than LULC change. The increases in runoff due to climate change follow a linear pattern for total or daily average runoff and for storm runoff.

LULC change is responsible for larger increases in total or average runoff at a yearly time scale than it is for runoff in individual storm events. In the same manner, LULC change is responsible for larger increases in total annual runoff than is climate change.

The effects of LULC change are somewhat moderated as a 1 K increase in temperature is responsible for a 0.67% lower increase in runoff for storm events and a 4.20% lower increase in daily average runoff.

The combined effect of climate and land cover change appears to be greater for total or average daily runoff than for individual storm events. It appears as though the two factors have a multiplicative effect upon one another, each compounding the effects of the other. This confirms the importance of both factors when considering flooding within urbanized watershed.

The greatest concern may still be climate change and its larger effect on storm events, which produce the floods that are of concern in highly populated, urbanized watersheds. To further explore the role of climate change and to confirm the relative magnitudes of the contributions of LULC and climate change, future studies should be performed in other urbanized watersheds. In doing so, relative contributions of changes in temperature and precipitation should be examined by running models with climate data that increase temperature and precipitation data individually and in combined scenarios. Additionally, work should be done to calibrate discharge to observed historical data for basins of interest in order to examine the absolute magnitudes of increases in runoff and discharge due to LULC and climate change. Future work should correct limitations of this study by modeling discharge within basins which can be calibrated to an outlet that has historical discharge data, use a different model or VIC in combination with another model to account for actual urbanization and impervious surfaces instead of using bare soil, and modeling more than two LULC scenarios to validate the linear increases in runoff observed by Olivera and DeFee (2007).

REFERENCES

Blöschl, G. et al., 2007. At what scales do climate variability and land cover change impact on flooding and low flows? Hydrological Processes, 21(9): 1241-1247.

Chen, H., Guo, S., Xu, C., Singh, V., 2007. Historical temporal trends of hydro-climatic variables and runoff response to climate variability and their relevance in water resource management in the Hanjiang basin. Journal of Hydrology, 344(3-4): 171-184.

Cuo, L., Lettenmaier, D.P., Alberti, M., Richey, J.E., 2009. Effects of a century of land cover and climate change on the hydrology of the Puget Sound basin. Hydrological Processes, 23(6): 907-933.

Fisher, D., 2012. America's Fastest Growing Cities, Forbes Magazine. <http://www.forbes.com/sites/danielfisher/2012/04/18/americas-fastest-growing-cities/>.

Fowler, A.M., Hennessy, K.J., 1995. Potential impacts of global warming on the frequency and magnitude of heavy precipitation. Nat Hazards, 11(3): 283-303.

Frei, C., Schär, C., Lüthi, D., Davies, H.C., 1998. Heavy precipitation processes in a warmer climate. Geophysical Research Letters, 25(9): 1431-1434.

Gao, H., Q. Tang, X. Shi, C. Zhu, T. J. Bohn, F. Su, J. Sheffield, M. Pan, D. P. Lettenmaier, and E. F. Wood, 2012. Water Budget Record from Variable Infiltration Capacity (VIC) Model. In Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records (in review). .

<http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Overview/ModelOverview.shtml>.

Gordon, H.B., Whetton, P.H., Pittock, A.B., Fowler, A.M., Haylock, M.R., 1992. Simulated changes in daily rainfall intensity due to the enhanced greenhouse effect: implications for extreme rainfall events. Climate Dynamics, 8(2): 83-102.

Hamlet, A.F., Lettenmaier, D.P., 2007. Effects of 20th century warming and climate variability on flood risk in the western U.S. Water Resources Research, 43(6): W06427.

Hydrology, UW, 2009. Downloads. University of Washington. <http://www.hydro.washington.edu/Lettenmaier/Models/VIC/SourceCode/Download.shtml>.

Hydrology, U.W., 2013. Routing: UH File. University of Washington. <http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Documentation/Routing/UH.shtml>.

Jiang, X., Yang, Z., 2012. Projected changes of temperature and precipitation in Texas from downscaled global climate models. Climate Research, 53(3): 229-244.

Kever, J., 5 April 2012. Harris leads nation's other counties in growth, Houston Chronicle. <http://www.chron.com/news/houston-texas/article/Houston-metro-area-breaks-into-the-Top-5-3460011.php>.

Knutson, T.R., Tuleya, R.E., 2004. Impact of CO2-induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization. Journal of Climate, 17(18): 3477-3495.

Legesse, D., Vallet-Coulomb, C., Francoise, G., 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. Journal of Hydrology, 275(1-2): 67-85.

Liang, X., Lettenmaier, D.P., Wood, E.F., 1996. One-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model. Journal of Geophysical Research, 101(D16): 21403-21,422.

Liang, X., Lettenmaier, D.P., Wood, E.F., Burges, S.J., 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research: Atmospheres (1984–2012), 99(D7): 14415-14428.

Liang, X., Wood, E.F., Lettenmaier, D.P., 1996. Surface soil moisture parameterization of the VIC-2L model: Evaluation and modification. Global and Planetary Change, 13(1): 195-206.

Maurer, E., Wood, A., Adam, J., Lettenmaier, D., Nijssen, B., 2002. A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States*. Journal of Climate, 15(22): 3237-3251.

Meehl, G.A. et al., 2000. Trends in Extreme Weather and Climate Events: Issues Related to Modeling Extremes in Projections of Future Climate Change*. Bulletin of the American Meteorological Society, 81(3): 427-436.

Olivera, F., DeFee, B.B., 2007. Urbanization and Its Effect On Runoff in the Whiteoak Bayou Watershed, Texas1. JAWRA Journal of the American Water Resources Association, 43(1): 170-182.

Pachauri, R.K., 2008. Climate change 2007. Synthesis report. Contribution of Working Groups I, II and III to the fourth assessment report.

Sheng, J., Wilson, J.P., 2009. Watershed urbanization and changing flood behavior across the Los Angeles metropolitan region. Nat Hazards, 48(1): 41-57.

Shi, P.-J. et al., 2007. The effect of land use/cover change on surface runoff in Shenzhen region, China. Catena, 69(1): 31-35.

Shiu, C.J., Liu, S.C., Fu, C., Dai, A., Sun, Y., 2012. How much do precipitation extremes change in a warming climate? Geophysical Research Letters, 39(17).

US, E.P.A., 2012. Buffalo San Jacinto Watershed -- 12040104, Surf Your Watershed. <http://cfpub.epa.gov/surf/huc.cfm?huc_code=12040104>.

USDA, 2013. Watershed Boundary Dataset (WBD) Seamless National Data. In: Service, N.R.C. (Ed.). <ftp://ftp.ftw.nrcs.usda.gov/wbd/>.

USGS, 2013. w100n40 GTOPO30. <http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30/w100n40>.

Wentz, F.J., Ricciardulli, L., Hilburn, K., Mears, C., 2007. How much more rain will global warming bring? Science, 317(5835): 233-235.